Large Scale QSO-galaxy correlations for radio loud and optically selected QSO samples

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ABSTRACT

We have studied the distribution of $B_J < 20.5$ galaxies from the ROE/NRL COSMOS/UKST catalogue around two samples of $z > 0.3$ QSOs with similar redshift distributions. The first sample is formed by 144 radio-loud QSOs from the Parkes Catalogue, and the other contains 167 optically selected QSOs extracted from the Large Bright Quasar Survey. It is found that there is a $\approx 99.0\%$ significance level excess of COSMOS/UKST galaxies around the PKS QSOs, whereas there is a marginal defect of galaxies around the LBQS QSOs. When the distribution of galaxies around both samples is compared, we found that there is an overdensity of galaxies around the PKS sample with respect to the LBQS sample anticorrelated with the distance from the QSOs at a 99.7% significance level. Although this result apparently agrees with the predictions of the multiple magnification bias, it is difficult to explain by gravitational lensing effects alone; dust in the foreground galaxies and selection effects in the detection of LBQS QSOs should be taken into account. It has been established that the lines of sight to PKS flat-spectrum QSOs go through significatively higher foreground galaxy densities than the directions to LBQS quasars, what may be partially related with the reported reddening of PKS QSOs.

Subject headings: gravitational lensing — large-scale structure — quasars: general

1. Introduction

In the last few years, several studies have established the existence of a statistical excess of line-of-sight companion galaxies around high redshift quasars. Although it has been

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suggested that these objects belong to clusters or groups which are physically associated to the quasars (Hintzen et al. 1991; Tyson 1986), in order to be detected at such high redshifts they should be undergoing strong luminosity evolution. This seems unlikely on the light of the recent data on galaxy evolution obtained through the study of absorption-selected galaxy samples (Steidel 1995), which shows that the most plausible (and often the unique) interpretation for many of these observations is the existence of a magnification bias caused by gravitational lensing (see the reviews Schneider et al. 1992; Schneider 1995; Wu 1995).

The density of a population of flux-limited background sources (e.g. QSOs) behind a gravitational lens is affected by the lens magnification μ in two opposite ways. One of the effects is purely geometrical: as the angular dimensions of a lensed patch of the sky are expanded by a factor μ, the physical size of a region observed through a fixed angular aperture will be smaller than in the absence of the lens. Because of this, the QSO surface density will decrease by a factor μ with respect to the unlensed background density Narayan 1989). On the other hand, the lens will magnify faint quasars (which would not have been detected otherwise) into the sample and increase the number of detected QSOs (Canizares 1981; Schneider 1986, etc.). If the slope of the quasar number-counts cumulative distribution is steep enough, this effect would dominate over the angular area expansion and there would be a net excess of QSOs behind the lens. Foreground galaxies trace the matter overdensities acting as lenses and thus there will be a correlation between the position in the sky of these galaxies (or other tracers of dark matter as clusters) and the background quasars. This QSO-galaxy correlation is characterized by the overdensity factor q (Schneider 1989), which is defined as the ratio of the QSO density behind a lens with magnification μ to the unperturbed density on the sky. Its dependence on the effective slope α of the QSO number counts distribution (which has the form $n(>S) \propto S^{-\alpha}$, or $n(<m) \propto 10^{0.4\alpha m}$) and the magnification μ can be expressed as (Narayan 1989)

$$q \propto \mu^{\alpha-1} \tag{1}$$

We see that the value of q critically depends on the number counts slope of the background sources. For instance, if the number counts are shallow enough, ($\alpha < 1$), there would be negative QSO-galaxy associations. It is clear that in order to detect strong, positive QSO-galaxy correlations due to the magnification bias, we have to use QSO samples with very steep number counts slopes. Borgeest et al. 1991 have shown that for a QSO sample which is flux-limited in two bands (with uncorrelated fluxes), α is substituted by α_{eff}, the sum of the number counts-flux slopes in those bands. This effect is called 'double magnification bias'. Since α_{eff} is usually > 1 for samples which are flux-limited in both the optical and radio bands (e.g. radio-loud QSOs), a strong positive QSO-galaxy correlation should be expected for them.

It is important to understand when QSO samples may be affected by the double magnification bias. The usual identification procedure for a X-ray or radio selected QSO sample involves setting up a flux threshold in the corresponding band and obtaining follow-up optical images and spectra of the QSO candidates. The observer is limited in this step by several circumstances (e.g. the sensitivity of the detectors or the telescope diameter), and even if the QSO sample was not intended to be optically selected, in the practice there will be an optical flux threshold for the QSOs to enter the sample. Therefore the existence of an explicit and homogeneus flux-limit in the optical band is not as essential for the presence of the magnification bias as the vaue of the effective slope of the unperturbed number counts. If this slope is steep enough, the effect should be detectable even in incomplete samples, and often more strongly than in complete catalogues: within such samples, the optically brightest QSOs (i.e., those more likely to be lensed) are usually the first to be identified, as they are easier to study spectroscopically or through direct imaging.

At small angular scales, ($\theta \lesssim$ few $''$) the existence of QSO-galaxy correlations is well documented for several QSO samples obtained with different selection criteria (Webster et al. 1988; see also Hartwick & Schade 1990 and Wu 1995 for reviews). As expected due to the double magnification bias effect, the correlations are stronger for radio-loud quasars (Thomas et al. 1994). In the cases where no correlation is found, e.g. for optically-selected and relatively faint quasars, the results are still consistent with the magnification bias effect and seem to be due to the shallowness of the QSO number counts distribution at its faint end (Wu 1994).

Hartwick & Schade 1990 reviewed the studies on QSO-galaxy correlations (on both small and large scales). After assuming that the galaxies forming the excess are physical companions to the QSO, they showed that while the amplitude of the radio-quiet QSO-galaxy correlation quickly declines at $z \gtrsim 0.6$, the inferred radio-loud QSO-galaxy correlation function steadily increases with redshift, independently of the limiting magnitude of the study. It should be noted that such an effect will be expected, if a considerable part of the galaxy excess around radio-loud QSOs is at lower redshifts. If a foreground group is erroneously considered to be physically associated with a QSO, the higher the redshift of the QSO, the stronger the 3-D clustering amplitude that will be inferred. This source of contamination should be taken into account carefully when carrying out these studies, as there is evidence that part of the detected excess around high redshift radio-loud QSOs is foreground and related with the magnification bias.

The association of quasars with foreground galaxies on scales of several arcmin may arise as a consequence of lensing by the large scale structure as proposed by Bartelmann

& Schneider 1991 (see also Schneider 1995 and references therein). Several authors have also investigated QSO-cluster correlations: Rodrigues-Williams & Hogan 1995, Seitz & Schneider 1995 and Wu & Han 1995. There are not many studies of large scale QSO-galaxy correlation, mainly because of the difficulty in obtaining apropriate, not biased, galaxy samples. Besides, the results of these studies may seem contradictory, as they radically differ depending on the QSO type and limiting magnitude.

Boyle et al. 1988 found a slight anticorrelation between the positions of optically selected QSOs and COSMOS galaxies. When they cross-correlated the QSOs with the galaxies belonging to clusters, the anticorrelation become highly significant (4σ) on $4'$ scales. Although this defect was interpreted as due to the presence of dust in the foreground clusters which obscured the quasars, the recent results of Maoz 1995 and Rodrigues-Williams & Hawkins 1995 have imposed limits on the amounts of dust in clusters which seem to contradict this explanation. It seems more natural, taking into account the rather faint flux-limit of the QSOs of Boyle et al. 1988 to explain this underdensity as a result of the magnification bias effect.

Smith et al. 1995 do not find any excess of foreground, $B_J < 20.5$ APM galaxies around a sample of $z > 0.3$ X-ray selected QSOs. It should be noted that although the objects in this sample are detected in two bands (X-ray and optical), the expected excess should not be increased by the double magnification bias effect, because the X-ray and optical fluxes are strongly correlated (Boyle & di Matteo 1996). For these QSOs, the overdensity should be roughly the same as for the optically selected ones.

On the other hand, there have been strong evidences of positive large scale associations of foreground galaxies with high redshift radio-loud QSOs. As e.g., between the radio-loud quasars from the 1Jy catalogue (Stickel et al. 1994) and the galaxies from the Lick (Fugmann 1990, Bartelmann & Schneider 1993), IRAS (Bartsch et al. 1996, Bartelmann & Schneider 1994) and APM (Benítez & Martínez-González 1995) catalogues. In the latter paper, we found that APM galaxies are correlated with the 1Jy QSO positions, but did not have enough statistics to reach the significance levels reported in the present paper. Unlike the COSMOS catalogue, the APM catalogue provides magnitudes in two filters, O(blue) and E(red). When we considered only the reddest, $O - E > 2$ galaxies, the overdensity reached a significance level of 99.1%. Afterwards, Odewahn & Aldering 1995 showed (using a similar, but much more processed catalog, the APS scans of POSS-I) that the galaxies which trace the high-density cluster and filamentary regions have redder $O - E$ colors than the galaxies drawn from low-density interfilamentary regions. If the fields containing Abell clusters were removed from the sample of Benítez & Martínez-González 1995, the results did not change significantly, so it seems that the detected effect was caused by the large

scale structure as a whole. Fort et al. 1995 confirmed the existence of gravitational lensing by the large scale structure by directly detecting the large foreground invisible matter condensations responsible for the magnification of the QSOs through the polarization produced by weak lensing in several 1Jy fields.

These differences in the nature of the QSO-galaxy associations for the several QSO types seem to arise quite naturally when we take into account the effects of the double magnification bias. There is not any strong correlation between the radio and optical fluxes for radio-loud quasars, so for these objects the overdensity will be $\propto \mu^{\alpha_{opt}+\alpha_{rad}-1}$ (Borgeest et al. 1991), where α_{opt} and α_{rad} are the number-counts slope in the optical and in radio respectively. If we assume that α_{opt} is roughly the same for radio-loud and optically selected QSOs (although this is far from being clear), the overdensity of foreground galaxies should be higher for the radio-loud QSOs. For optically and X-ray selected samples (because of the X-ray-optical flux correlation), α_{eff} and therefore the overdensity, will be smaller.

In any case, it is difficult to compare conclusively the published analyses of QSO-galaxy correlations. They have been performed using galaxy samples obtained with different filters and magnitude limits, and which therefore may not trace equally the matter distribution because of color and/or morphological segregation or varying depths. Besides, the QSO samples differ widely in their redshift distributions. As the magnification of a background source depends on its redshift, QSO samples with different redshift distributions will not be magnified equally by the same population of lenses. It would thus be desirable, in order to disentangle these factors from the effects due to the magnification bias caused by gravitational lensing, to reproduce the mentioned studies using galaxy samples obtained with the same selection criteria and QSO samples which are similarly distributed in redshift. This is the purpose of the present paper: we shall study and compare the distribution of COSMOS/UKST galaxies around two QSO samples, one radio-loud and the other radio-quiet with practically identical redshift distributions.

It is also interesting to mention in this context the results of Webster et al. 1995. These authors observed that a sample of flat-spectrum radio-loud quasars from the Parkes catalogue (Wright & Otrupcek, 1990) displays a wide range of $B_J - K$ colours, apparently arising from the presence of varying amounts of dust along the line of sight. Optically selected quasars do not present such a scatter in $B_J - K$ and lie at the lower envelope of the $B_J - K$ colours, so Webster and collaborators suggested that the selection criteria used in optical surveys miss the reddest quasars. Although there seems to be several other, more plausible, reasons for this phenomenon (see for instance Boyle & di Matteo 1996), it is not adventurous to suppose that it may be partially related to the differences between the foreground projected environments of radio-loud and optically selected quasars. If a

considerable part of the absorbing dust belongs to foreground galaxies, a greater density of these galaxies would imply more reddening.

The structure of the paper is the following: Section 2 describes the selection procedures of both QSO samples and galaxy fields and discuss the possible bias which could have been introduced in the data. Section 3 is devoted to the discussion of the statistical methods used in the literature for the study of this problem and applies them to our data. Section 4 discusses the results obtained in Sec 3. Section 5 lists the main conclusions of our work.

2. The Data

As we have explained above, the aim of our paper is the study of the distribution of foreground galaxies around two QSO samples, one radio-loud and the other radio quiet, which have similar redshift distributions. It would also be interesting to find out if these differences in the foreground galaxy density occur for the QSO samples of Webster et al. 1995. This, as we have mentioned, could be related to the differential reddening of the radio-loud quasars. Therefore, in order to form a radio-loud sample suitable for our purposes but as similar as possible to the one used by Webster et al. 1995, we collect all the quasars from the PKS catalogue which are listed in the Veron-Cetty & Veron 1996 QSO catalogue and obey the following constraints: a) flux > 0.5Jy at 11cm; b) $-45 < \delta < 10$ and c) galactic latitude $|b| > 20$. So far, we do not constrain the radio spectral index of the quasars. This yields a preliminary sample of 276 quasars.

The galaxy sample is taken from the ROE/NRL COSMOS/UKST Southern Sky object catalogue, (see Yentis et al. 1992 and references therein). It contains the objects detected in the COSMOS scans of the glass copies of the ESO/SERC blue survey plates. The UKST survey is organized in 6×6 square degree fields on a 5 degree grid and covers the zone $-90 < \delta < 0$ excluding a ± 10 deg zone in the galactic plane. COSMOS scans cover only 5.4×5.4 square degrees of a UKST field. The scan pixel size is about 1 arcsec. Several parameters are supplied for each detected object, including the centroid in both sky and plate coordinates, B_J magnitude and the star-galaxy image classification down to a limiting magnitude of $B_J \approx 21$.

We are going to study the galaxy distribution in $15'$ radius fields centered on the quasars of our sample. Due to several factors as vignetting and optical distorsions, the quality of the object classification and photometry in Schmidt plate based surveys degrades with increasing plate radius. Therefore, we constrain our fields to be at a distance from the plate center of $r = \sqrt{\Delta x^2 + \Delta y^2} < 2.5$ degrees. Besides, to avoid the presence of fields

which extend over two plates we further restrict our sample to have $|\Delta x_k|, |\Delta y_k| < 2.25$ degrees, where Δx_k and Δy_k are the distances, in the α and δ directions respectively, from the center of the plate (because of the UKST survey declination limits, this also constrains our quasar sample to have $\delta < 2.25$). After visually inspecting all the fields, several of them (6) are excluded from the final sample because they present meteorite traces. We end up with 147 circular fields with a $15'$ radius centered on an equal number of Parkes Quasars. This subsample of radio-loud quasars is, as far as we know, not biased towards the presence of an excess of foreground galaxies, which is the essential point for our investigation. In order to avoid contamination from galaxies physically associated with the quasars, we also exclude three $z < 0.3$ quasars from our radio-loud sample (Smith et al. 1995 point out that only 5% of $B_J < 20.5$ galaxies have $z > 0.3$), which is finally formed by 144 fields.

We have excluded a region of $12''$ around the positions of the quasars (which may have an uncertainty up to ± 5 arcsec). This is done to avoid the possibility of counting the quasar as a galaxy (there are six cases in which the quasar is classified as an extended object) and because of the great number of 'blended' objects at the quasar position. Most of these pairs of objects are classified as 'stars' when deblended, but taking into account the pixel resolution, it would be desirable to examine the original plates or, better yet, perform high resolution CCD imaging in order to properly deblend and classify these objects as many of them could be galaxies.

The optically selected sample is taken from the Large Bright Quasar Survey as in Webster et al. 1995. This prism-selected catalogue contains 1055 quasars brighter than $B_J \approx 18.6$ on several equatorial and southern fields (for details see Hewett et al. 1995). In order to form an optically selected subsample of quasars we have begun by choosing the 288 quasars from the LBQS catalogue which were closest in redshift to our final sample of 144 PKS quasars. We impose to them exactly the same constraints in sky and plate position as to the radio-loud quasar fields. Finally we visually examined the fields and excluded six of them because of meteorite traces. The resulting number of fields is 167. As the LBQS extends over relatively small areas of the sky, several of these fields overlap. We have checked that their exclusion from the statistical tests performed below does not affect significantly the result, so we leave them in the sample.

The resulting redshift distribution for both QSO samples is plotted in Fig 1. A Kolmogorov-Smirnov test cannot distinguish between them at a 94.5% significance level. We merge all the fields in each sample into two 'superfields' which contain all the objects classified as galaxies with $B_J < 20.5$. This is a reasonable limiting magnitude, and has been already used by other investigators (Smith et al. 1995). The PKS merged field contains 15235 galaxies whereas the LBQS field only contains 14266. This is a difference of 24%

in the average object background density, well over a possible Poissonian fluctuation, and seems to be caused by the presence of misclassified stars in our galaxy sample at low galactic latitudes. The Parkes fields extend over a much wider range of galactic latitudes ($|b| > 20^o$) than the LBQS ones, which are limited to high galactic latitudes ($|b| > 45^o$) and thus much less affected. In fact, we measure the existence of a significant anticorrelation between the absolute value of the galactic latitude $|b_k|$ of the fields and the total number of objects in each field N_{gal}. The correlation is still stronger between N_{gal} and $\sec(90 - |b|)$, as shown in Fig. 2, with a correlation coefficient $\rho = 0.4, (p > 99.99\%)$. This contamination should be randomly distributed over the field and would lower the significance of any possible correlation and make it more difficult to detect. In order to check this, we have correlated the overdensity n_{in}/n_{out} of objects within the inner half of every individual field, (n_{in} is the number of objects within the inner half of the field surface and n_{out} is the number of objects in the outer half) with $\sec(90^o - |b|)$, as can be seen in Fig. 3. If anything, there might be a slight anticorrelation (the Spearman's rank correlation test only gives a significance of 80%) in the sense that the fields with more star contamination are the ones which show less excess of galaxies in the inner half of the field. This is what could be expected if there were a genuine galaxy excess close to the QSO positions; this excess should be diluted by the presence of stars randomly distributed with respect to the QSOs. Excluding the fields with $|b| \leq 30^o$, as in Smith et al. 1995, does not change significantly the main results, as we show in Fig 4. Because of this contamination by stars, there is a slight bias in the data which makes harder to detect QSO-galaxy correlations for the PKS QSOs than for the LBQS ones. We have also checked that there are no other correlations between N_k and q_k and other possible relevant parameters as the plate or sky position of the fields.

3. Statistical Analysis

The study of QSO-galaxy correlations due to the magnification bias effect is complicated by several circumstances. The amplitude of the correlation function w_{qg} is expected to be rather weak, and strongly dependent on the limiting magnitude of the galaxies and the QSOs. Besides, the shape of w_{qg} as a function of θ is unknown (it seems that the interesting theoretical estimation of Bartelmann 1995 has not been confirmed empirically by Bartsch et al. 1996).

In the past, several methods have been used to detect and statistically establish the existence of these correlations. One of the most simple and widespread approaches has consisted in counting the number of galaxies N_{in} in a somehow arbitrarily defined region centered on the quasars and comparing the value found with its statistical expectation,

which is measured either from the outer regions of the fields or from some other comparison fields which are assumed to have the same density of galaxies on average. The significance can be inferred empirically (Benítez & Martínez-González 1995) or just by considering that N has a poissonian distribution with $\sqrt{N}$ rms. This last assumption seems to hold well in some cases, when the number of individual fields is very large, but for other samples, usually smaller, the rms is found to be $\alpha\sqrt{N}$, where $\alpha \approx 1.1 - 1.5$ (Benítez et al. 1995). A shortcoming of this method is that it does not extract all the information contained in the fields as it only explores the distribution of galaxies around the quasar in a small number of scales, and often uses the rest of the field just to determine the average density. Besides, if the correlation scale is comparable with the dimensions of the fields, the average density measured on the fields would be increased with respect to the unperturbed one and thus an artificially lowered signification will be obtained.

Another method, the rank-correlation test was used in Bartelmann & Schneider 1993, Bartelmann & Schneider 1994. All the individual galaxy fields are merged into a single 'superfield', which is subsequently divided into N_{bins} annular intervals of equal surface. A Spearman's rank order test is applied to determine if the number of galaxies in each bin $n_i, (i = 1, N_{bins})$ is anticorrelated with the bin radius r_i. This test does not require any assumption about the underlying probability distribution of the galaxies and takes into account all the information contained in the fields. However it has several drawbacks. The rings have all equal surface, so we end up with more bins in the outer parts of the fields, which are less sensitive from the point of view of detecting the correlation. Besides, the method only 'senses' the relative ordering of n_i and r_i over the whole field. For instance if $w_{qg}(\theta)$ is very steep and goes quickly to zero, there will be only a few bins clearly over the average in the central region, and the correlation coefficient could then be dominated by the more numerous outer bins with nearly no excess galaxies. The value of the correlation coefficient and its significance, depend thus critically on the number of chosen bins and the dimension of the fields. However, this test can still be useful if the correlation scale is similar to the scale of the field.

Recently, Bartsch et al. (1996) have introduced the weighted-average test. They define the estimator r_g as

$$r_g = \frac{1}{N}\sum_{j=1}^{N} g(\theta_j), \tag{2}$$

where N is the total number of galaxies in the merged field, and θ_j are the radius from the QSO of each galaxy. They show, under certain general assumptions, that if the galaxies in the merged field are distributed following a known QSO-galaxy correlation function $w_{gq}(\theta)$, for $g(\theta) \propto w_{gq}(\theta)$ the quantity r_g is optimized to distinguish such a distribution of galaxies from a random one. They take $w_{gq}(\theta) = (0.24 + h\theta/deg)^{-2.4}$ from the theoretical results

of Bartelmann 1995 ($h = H_o/100$ Mpc km s^{-1}), and show with simulated fields that this method is slightly more sensitive than Spearman's rank order test. However, when they study the correlation between IRAS galaxies and the QSOs from the 1Jy catalogue with the weighted-average test they obtain a much higher significance for their result than using the rank order test. They conclude that although the IRAS galaxies do not seem to be clustered around the QSOs following Bartelmann's correlation function, the weighted average method seems to be a much more efficient estimator than the rank order test. This is not surprising if we consider that, when calculating the estimator r_g (as long as we use a steep enough form for $g(\theta)$) this test gives a much higher weight to the galaxies closer to the QSO, that is, to the regions where the excess signal-to-noise is higher. An extreme case would be to use a top hat function with a given width θ_o as $g(\theta)$ (which would be equivalent to counting galaxies in a central circle of dimension θ_o). This arbitrariness in the choice of $g(\theta)$ when we do not know the real shape of the QSO-galaxy correlation is a drawback of this method. Another problem is that the probability distribution of r_g is unknown a priori. Because of that, the significance has to be determined using simulations, and as we have seen before, the real galaxy distribution is not always easy to know and model. Nevertheless, when we know theoretically the correlation, this test should be optimal, and it may also be useful in many other cases.

We have applied a variant of the rank order test to study the distribution of galaxies around our PKS and LBQS samples. We also use the Spearman's rank order test as statistical estimator (in the implementation of Press et al. 1992), but instead of fixing a number of bins and dividing the field in rings of equal surface as in Bartelmann & Schneider 1994, the variables to be correlated will be $w(\theta_i)$ and θ_i, where $w(\theta_i)$ is the value of the empirically determined angular correlation function in rings of equal width and θ_i is the distance of the bins from the QSO. Now, in general, each ring will have a different number of galaxies, but the values of θ_i are going to be uniformly distributed in radius, and thus we will not give more weight to the outer regions of the field. As a statistical estimator we shall use Z_d, the number of times by which D, the so-called sum squared difference of ranks, deviates from its null-hypothesis expected value. D has an approximately normal distribution and is defined as

$$D = \sum_{i=1}^{N} (R_i - S_i)^2 \tag{3}$$

where R_i is the rank of the radius of the i-th ring and S_i is the rank of the density in that same ring. Trying to avoid the dependence of the result on the concrete number of bins, we have followed this procedure: we have chosen a minimal ring width ($0.4'$) in order to have at least ≈ 20 galaxies in the first ring, and a maximal width ($0.75'$) so that there are at least 20 rings within the field. Then we perform 8 different binnings changing the ring

width in steps of $0.05'$, estimate Z_d for each of them and calculate its average $< Z_d >$. This estimator should be very robust as it does not depend so strongly on the concrete value obtained for a binning, and the significance can be estimated directly from the value of Z_d without the need of simulations. The value for the PKS field is $< Z_d >= 2.33\sigma$, $p = 99.0\%$ and for the LBQS field $< Z_d >= -0.68\sigma$, $p = 75.2\%$. We have also confirmed this by estimating $< Z_d >$ for 10^5 simulations with randomly distributed galaxies for each of both fields: the empirical significance for the PKS field is $p = 99.01\%$ whereas the LBQS field gives $p = 72.46\%$. This similarity in the values of the probabilities also confirms that the distribution of the galaxies in the fields is practically Poissonian. The QSO-galaxy correlation function for the PKS and LBQS sample is shown in Fig. 4 and 5 respectively. Error bars are poissonian and the bin width is $0.75'$. In Fig. 4 we also show, without error bars, the correlation function obtained for the PKS fields with $|b| > 30^o$

In order to further test our results, we have also applied Bartsch et al. (1996) test to our data using Bartelmann's $g(\theta)$ and have estimated the significance with 10^5 simulated fields for each sample with the same number of galaxies as the real fields randomly distributed. Strictly speaking this is an approximation, as the galaxies are clustered among themselves, but we have studied the number of galaxies on rings of equal surface (excluding a few central rings) and their distribution is marginally consistent with being Gaussian with a rms $\approx \sqrt{N}$, what is not surprising if we take into account the great number of fields contributing to each bin. The existence of a positive QSO-galaxy correlation for the PKS sample is detected at a significance level of 98.85%. On the other hand, when we apply this test to the LBQS merged field, a slight anti-correlation is found at a level of 88.85%. These results are comparable to the ones obtained with the previous test. We have also tried other arbitrarily chosen variants of the function $g(\theta)$ to see the dependence of significance of the PKS excess on the concrete shape of $g(\theta)$: a Gaussian with a $2'$ width (analogous to a box of this size) yields $p = 99.66\%$ and a $\propto \theta^{-0.8}$ law (the slope of the galaxy-galaxy correlation function) gives $p = 99.5\%$. We see that for our galaxies, the shape of $g(\theta)$ proposed by Bartelmann is not optimal, and the significance depends sensitively on the shape of the function. However, tinkering with the form of $g(\theta)$ may be dangerous, as it could lead to creating an artificially high significance if we overadjust the shape of the function to the data.

Thus, it seems that there is a positive QSO-galaxy correlation in the PKS fields, and what appears to be a slight anticorrelation in the LBQS ones. In order to measure how much these two radial distributions differ, we have performed a series of binnings as the one described above for our test and defined q_i in each ring as $q_i \propto n_i^{PKS}/n_i^{LBQS}$, where n_i^{PKS} is the number of objects in each ring of the PKS field and n_i^{LBQS} is the number of objects in the same bin of the LBQS field, and normalize by the mean density of each field. We apply

the rank order test to all the resulting sequences of q_i and bin radii r_i as described above and find that $< Z_d >= 2.77$, $p = 99.7\%$. 10^5 simulations of field pairs give a significance of $p = 99.74$. This means that the density of foreground galaxies around the radio-loud quasars is higher than in front of the optically selected sample, and is anticorrelated with the distance from the QSOs at a 99.7% significance level.

4. Discussion

As shown above, we have confirmed the existence of large scale positive correlations between high-redshift radio-loud QSOs and foreground galaxies, whereas for optically selected QSOs with the same redshift distribution the correlation is null or even negative. Can these results be explained by the double magnification bias mentioned in the introduction? In order to answer this question the value of the number-counts distribution slopes in expression (1) must be determined. These slopes can be estimated from the empirical distribution functions of our QSO samples. The cumulative number-radio flux distribution for the PKS QSOs is plotted in Fig. 6. A linear squares fit gives an approximate slope $\alpha_{rad}^{PKS} \approx 1.6$. The histogram of the distribution of B_J magnitudes for the LBQS and the PKS QSOs is plotted in Fig 7a. For the PKS QSOs we do not use the magnitudes quoted in Veron-Cetty & Veron 1996 as they have been obtained with different filters and photometric systems. Instead, we have obtained B_J magnitudes from the ROE/NRL COSMOS/UKST catalog, which should be reasonably homogeneous and accurate for $16 < B_J < 20.5$, apart from the intrinsic variability of the QSOs. Fig. 7a shows that PKS QSOs extend over a wider range of magnitudes than the LBQS ones, which have $B_J \lesssim 18.6$. In Fig 7b we show the cumulative distributions of both QSO samples, $N(< B_J)$ as a function of B_J. The LBQS distribution (crosses) can be well aproximated by a power law $\propto 10^{0.4\alpha_{opt}^{LBQS}}$ with $\alpha_{opt}^{LBQS} \approx 2.5$. The PKS distribution (filled squares) is more problematic and cannot be approximated reasonably by a single power law. Although at brighter magnitudes it seems to have a slope similar to the LBQS ones, it quickly flattens and has a long tail towards faint magnitudes. Due to the incompleteness of the PKS sample, this distribution can be interpreted in two ways: either the flattening is caused by the growing incompleteness at fainter optical magnitudes and the slope of the underlying unperturbed distribution for the radio loud QSOs is the same as for LBQS ones, or the distribution function is intrisically shallow, and we are approximately observing its true form. Fortunately this is not a critical question; as it will be shown below, the difference between the slope values obtained in both cases is not enough to change significantly our main conclusions about the causes of the overdensity. Then, we roughly estimate the optical slope for the PKS distribution function with a linear squares fit between $16 < B_J < 17.75$

which yields $\alpha_{opt}^{PKS} \approx 1.9$. These slopes imply an overdensity of galaxies around the LBQS and PKS QSOs

$$q^{LBQS} = \mu^{\alpha_{opt}^{LBQS}-1} \approx \mu^{1.5}$$
$$q^{PKS} = \mu^{\alpha_{opt}^{PKS}+\alpha_{rad}^{PKS}-1} \approx \mu^{2.5} \tag{4}$$

That is, $q^{PKS}/q^{LBQS} \approx \mu$. At e.g. $\theta = 2'$, for the LBQS we found $q^{LBQS} = 0.968 \pm 0.063$. This yields a value for the magnification $\mu = 0.98 \pm 0.04$. Then for the PKS QSOs, the overdensity should be $\approx 0.95 \pm 0.1$. However at $\theta = 2'$, we measure $q_{PKS} = 1.164 \pm 0.061$. If we assume that the intrinsic PKS B_J number-counts slope is the same as for the LBQS QSOs, $\alpha_{opt}^{PKS} = 2.5$, we still cannot make both overdensities agree with a same magnification. In order to obtain these results with 'pure' gravitational lensing, a slope $\alpha_{PKS}^{opt} > 4$ would be needed. For smaller scales, the situation does not change, since q^{PKS}/q^{LBQS} is still higher. Therefore, we must conclude that it is unlikely that the multiple magnification bias alone explains the results found.

As mentioned above, some authors have explained the optically selected QSO-cluster anticorrelations as due to the existence of dust in clusters (Maoz 1995 and references therein). What would be the expected overdensity when we consider the combined effects of magnification and dust absorption? Let's consider a patch of the sky which has an average magnification of μ for background sources and an average flux extinction of τ for a given optical band, i.e. the observed flux S from the background sources in that band would be $S \approx (1-\tau)S_o$, where S_o is the flux that we would measure in the absence of absorption. If we consider that the radio emission suffers no attenuation by the dust, the overdensity estimations for our samples would be

$$q^{PKS} = \mu^{\alpha_{opt}^{PKS}+\alpha_{rad}^{PKS}-1}(1-\tau)^{\alpha_{opt}^{PKS}} \approx \mu^{2.5}(1-\tau)^{1.9}$$
$$q^{LBQS} = \mu^{\alpha_{opt}^{LBQS}-1}(1-\tau)^{\alpha_{opt}^{LBQS}} \approx \mu^{1.5}(1-\tau)^{2.5} \tag{5}$$

Therefore, from our results on scales of $2'$ we find $\mu \approx 1.139$, and $\tau \approx 0.089$. This extinction is consistent with the results of Maoz 1995. Although these values should be considered only as rough estimations, they show that considering dust absorption together with the multiple magnification bias produces new qualitative effects in the behavior of the overdensities of the different QSO types. The strength of the overdensity is attenuated in both samples of QSOs, but the effect is stronger for the LBQS QSOs, which have a steeper optical counts slope. If we consider that the dust approximately traces the matter potential wells acting as lenses, i.e. that there is a strong correlation between magnification and extinction, the

QSOs which are more magnified are also the ones which are more absorbed. However, if the product $\mu(1-\tau)$ is greater than unity, the net effect for each QSO will be a flux increment.

An alternative explanation is the existence of the bias suggested by Romani & Maoz 1992 and Maoz 1995. They interpret that the avoidance of foreground clusters by optically selected QSOs is probably a selection effect due to the difficulty in identyfing quasars in crowded fields. In that case, apart from the slight QSO-galaxy anticorrelation generated by this effect, the LBQS samples would avoid the zones where the lensing by the large scale structure is stronger and thus their average magnification μ would be smaller than that of the PKS, which would not be affected by this selection bias. Besides, if dust and magnification are correlated, radio-loud QSOs would also be more reddened on average than optically selected QSOs.

Regarding flat-spectrum QSOs, if we set an additional constraint for our QSOs, $\gamma > -0.5$, where γ is the slope of the spectral energy distribution, the resulting sample of 107 $z > 0.3$ QSOs should be a fair representation of the radio-loud sample used by Webster et al. 1995 for the study of reddening in QSOs. We apply again our rank correlation test to the field obtained by merging these 107 fields and conclude that the COSMOS/UKST galaxies are correlated with flat-spectrum QSOs at a 98.5% level. The QSO-galaxy correlation function is plotted in Fig. 8 with $0.75'$ bins. The value of the overdensity is similar, but as we have now fewer fields, the significance level is lower. Nevertheless, if we take into account the small amounts of dust allowed by the observations of Maoz 1995, it seems very unlikely that all the reddening measured by Webster et al. 1995 for the PKS QSOs is due to dust absorption by foreground galaxies, although in some cases this effect could contribute considerably, as it has been shown by Stickel et al. 1996. This question could be clarified by cross-correlating the reddening of the QSOs with the density of foreground galaxies on small scales.

5. Conclusions

We have studied the clustering of galaxies from the ROE/NRL COSMOS/UKST catalogue up to 15 $'$ scales around two QSO samples with $z > 0.3$. One of them contains 144 radio-loud QSOs from the Parkes Catalogue, and the other is formed by 167 optically selected QSOs obtained from the Large Bright Quasar Survey.

There is a $\approx 99.0\%$ significance level excess of COSMOS $B_J < 20.5$ galaxies around the PKS QSOs, whereas there is a slight defect of galaxies around the LBQS QSOs. We have compared the distribution of galaxies around both samples, and found that there is

an overdensity around the PKS sample with respect to the LBQS sample anticorrelated with the distance from the QSO at a 99.7% significance level. Whilst this result could be thought to agree qualitatively with the theoretical predictions of the multiple magnification bias effect, we show that it is difficult to explain it through gravitational lensing effects alone, and dust in the foreground galaxies and/or selection effects in the detection of LBQS QSOs must be considered.

Finally, we have established that the lines of sight to PKS flat-spectrum QSOs go through significantly higher foreground galaxy densities than the directions to LBQS quasars. This may be related, at least partially, with the reddening of the PKS QSOs observed by Webster et al. 1995.

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Fig. 1.— Redshift distributions of the PKS (solid line histogram) and LBQS (dashed line histogram) QSOs in our samples. The vertical axis show the fraction of QSOs in each redshift bin.

Fig. 2.— The total number of objects classified as galaxies in each field, N_{gal}, versus $\sec(90^o - |b|)$, where b is the field galactic latitude. The continuous line represents the linear least squares fit, with a correlation coefficient $\rho = 0.4$ and a significance $p > 99.99\%$). Crosses and filled squares represent LBQS and PKS QSOs respectively.

Fig. 3.— n_{in}/n_{out} vs. $\sec(90^o - |b|)$. n_{in}/n_{out} is the ratio between the number of galaxies in the inner half of each field n_{in} and the number of galaxies in the outer half n_{out}. b is the galactic latitude of each field.

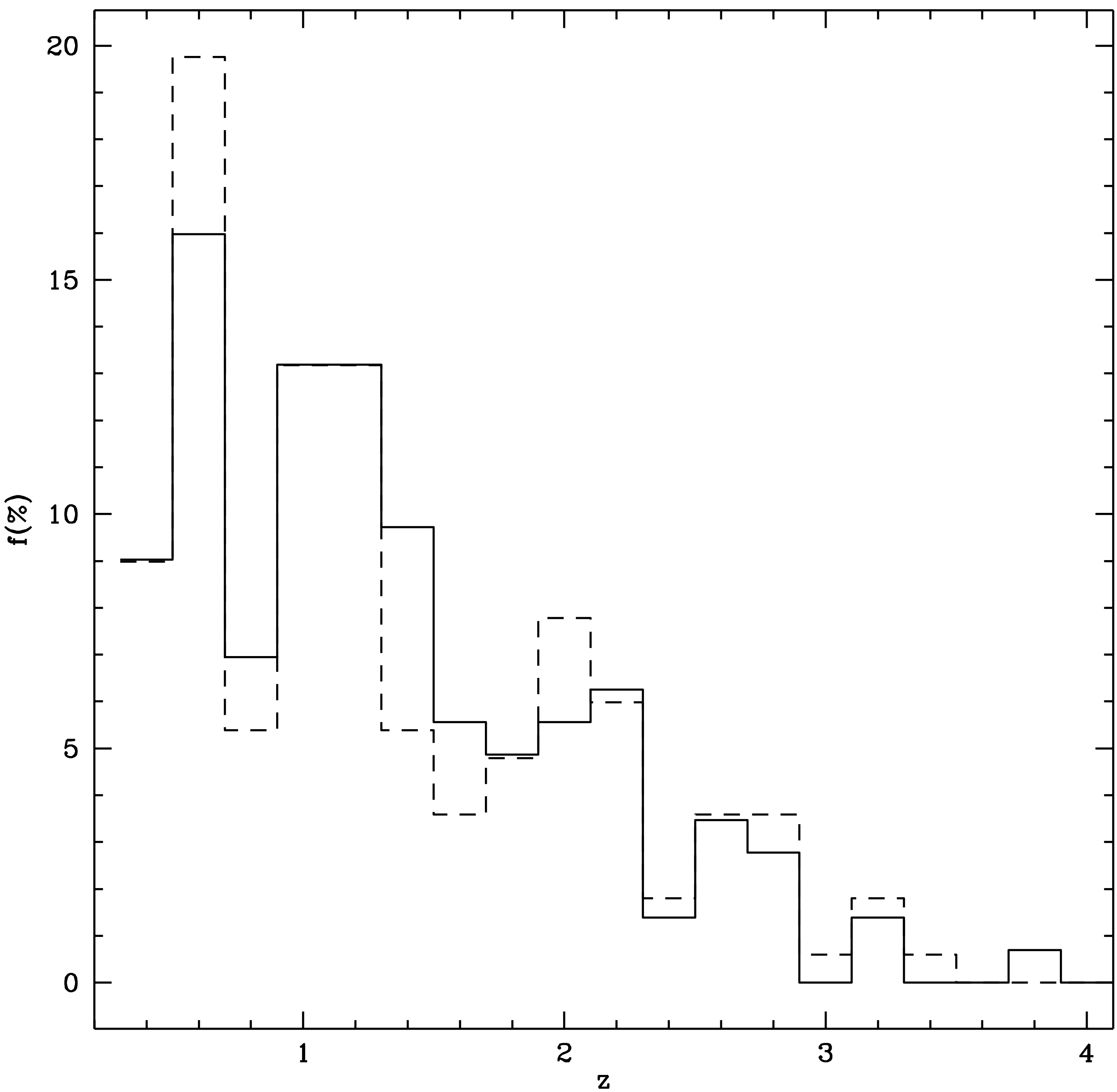
Fig. 4.— QSO-galaxy correlation for the PKS sample (continuous line). Error bars are poissonian and the bin width is approximately $0.75'$. The dotted line, with no error bars, represents the correlation function for a subsample of the PKS QSOs with $|b| > 30^o$.

Fig. 5.— QSO-galaxy correlation for the LBQS sample. Error bars are poissonian and the bin width is approximately $0.75'$.

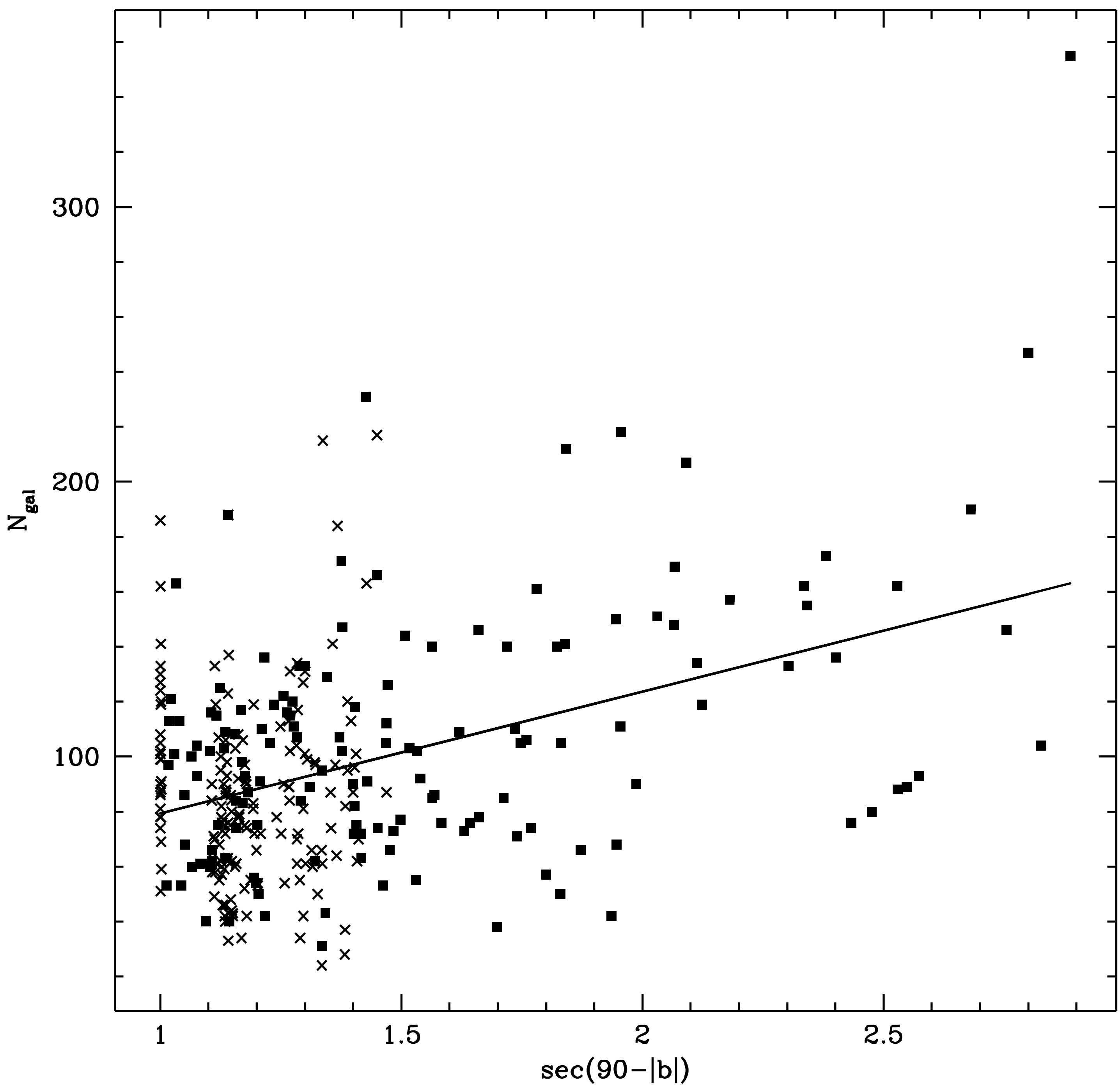
Fig. 6.— Logarithmic plot of the cumulative number counts–radio flux distribution $N(> S)$ for the PKS QSOs (dotted line). The continuous line is a linear least squares fit which yields a slope $\alpha_{rad}^{PKS} = 1.58$

Fig. 7.— a) Histograms of the magnitude distribution for the PKS (solid line) and LBQS (dashed line) QSOs. b) Cumulative number counts magnitude plot for the LBQS (crosses) and PKS (filled squares) QSOs as a function of B_J. The LBQS distribution is fitted by a power law $\propto 10^{0.4\alpha_{opt}^{LBQS}}$ with $\alpha_{opt}^{LBQS} \approx 2.5$.

Fig. 8.— QSO-galaxy correlation for the flat spectrum QSOs in the PKS sample. Error bars are poissonian and the bin width is $0.75'$.



f(%)
20
15
10
5
0
1
2
3
4
z



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200
100
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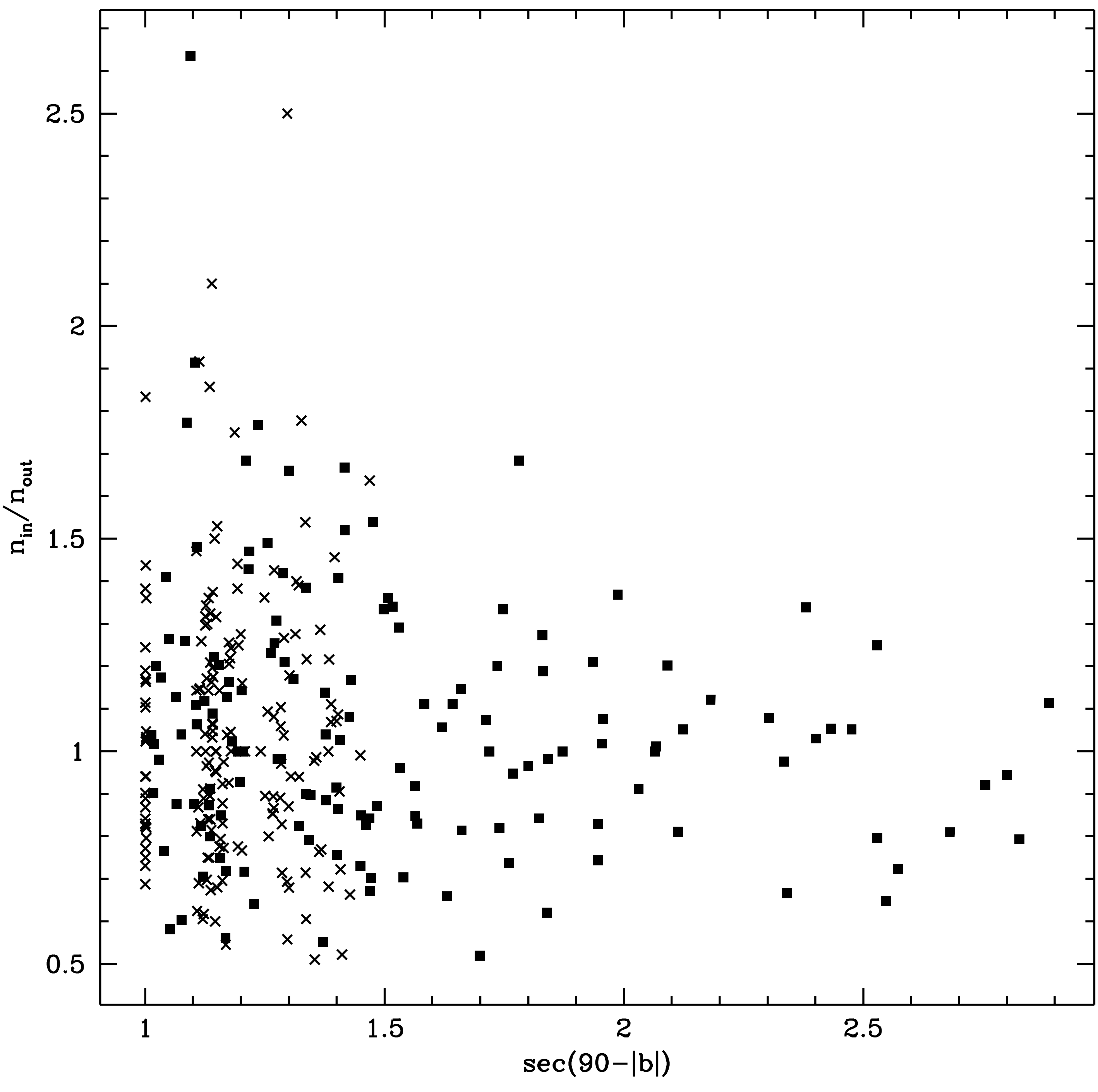
1.5
2
2.5
N_{gal}
sec(90−|b|)



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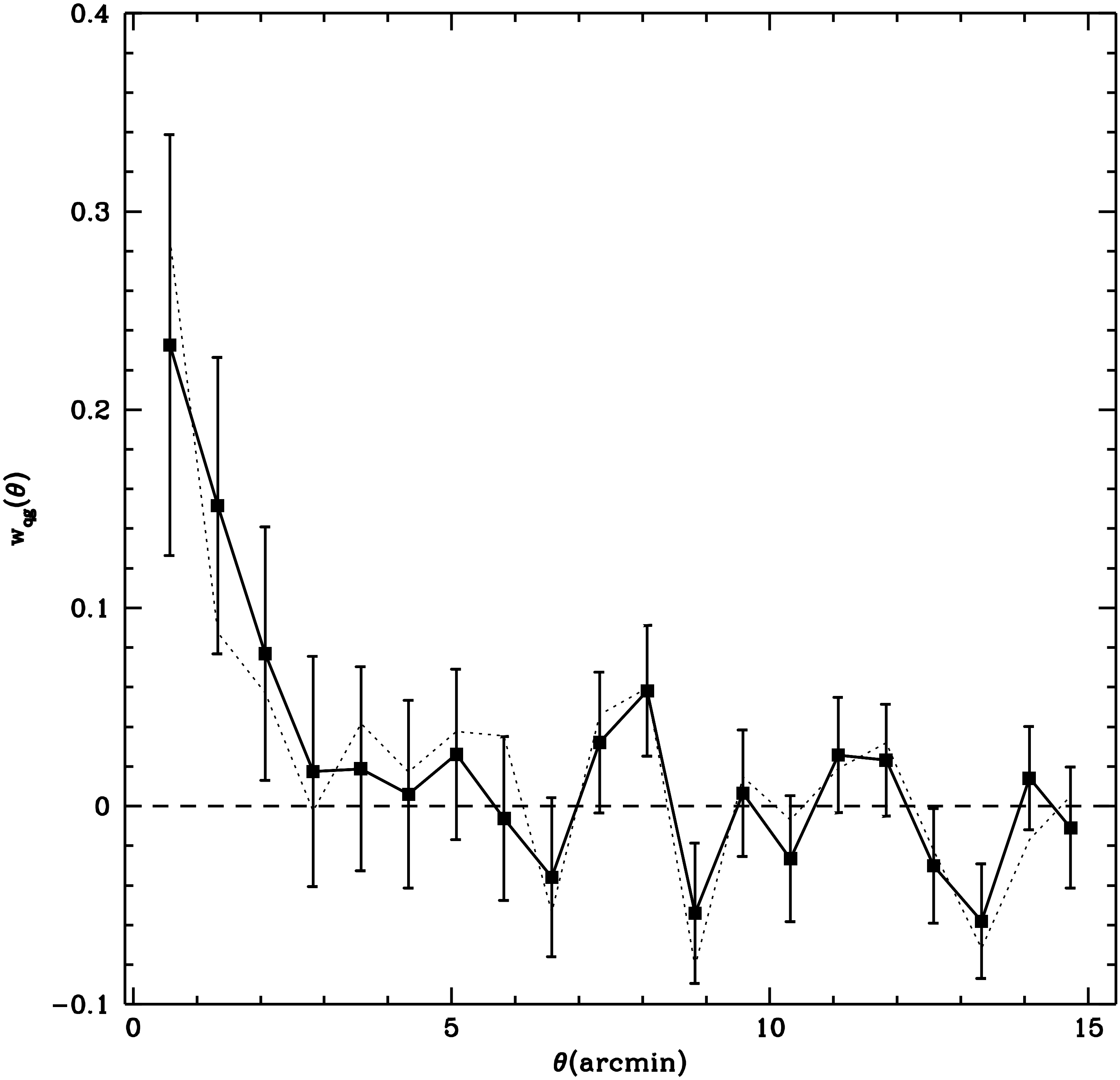
2
1.5
1
0.5
n_{in}/n_{out}
1
1.5
2
2.5
sec(90−|b|)



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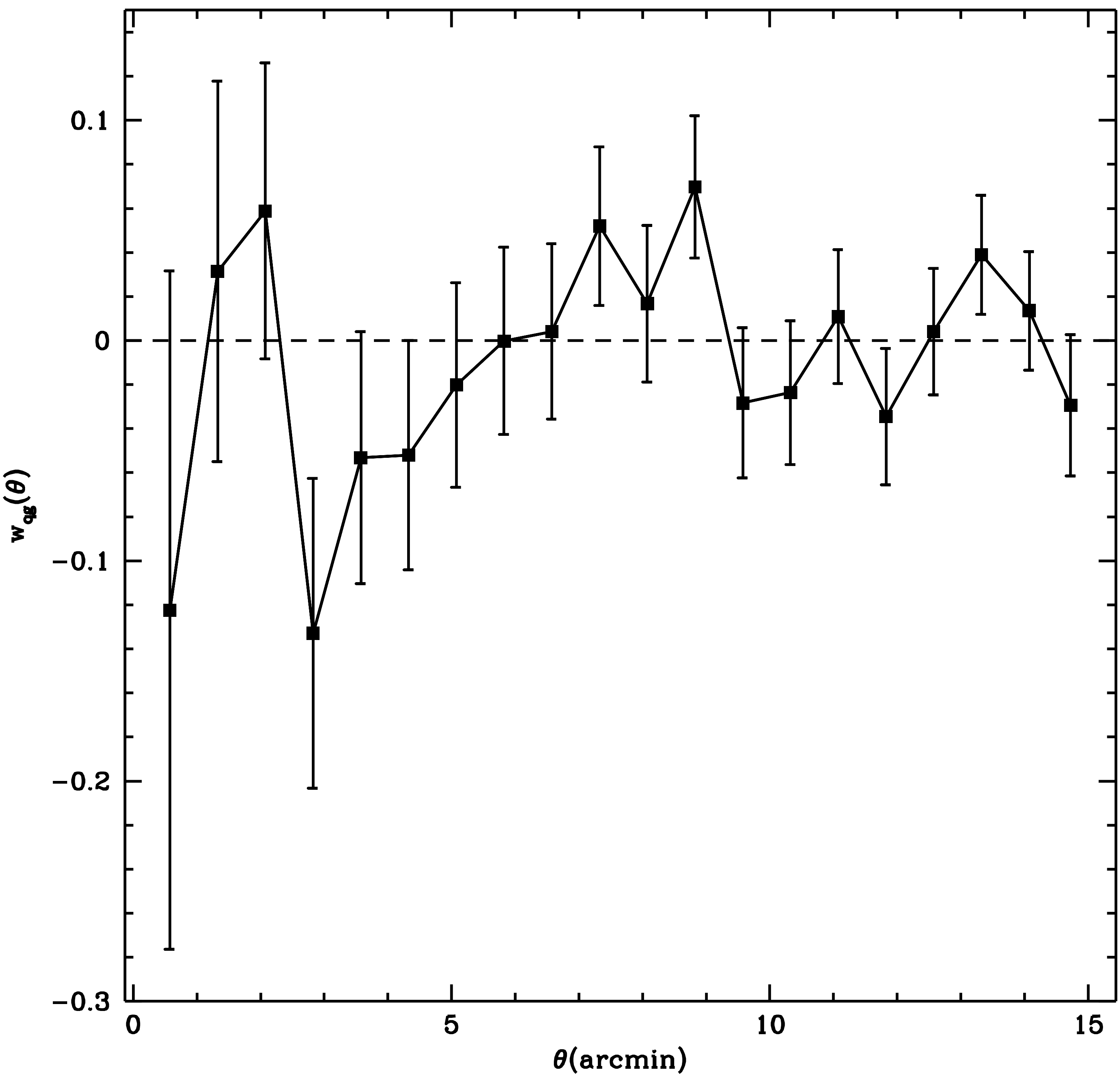
0.3
0.2
0.1
0
−0.1
0
5
10
15
$w_{qg}(\theta)$
θ(arcmin)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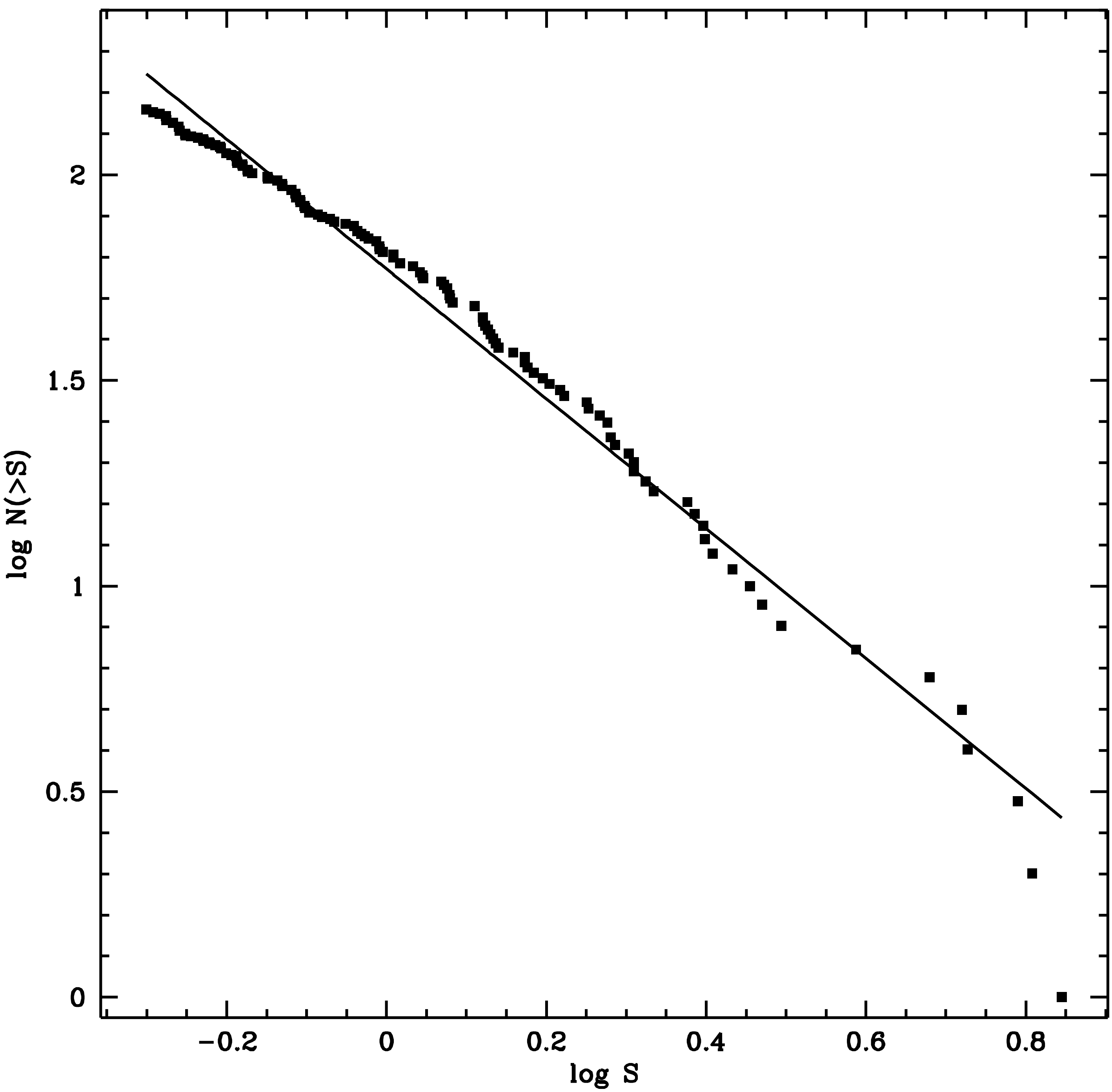
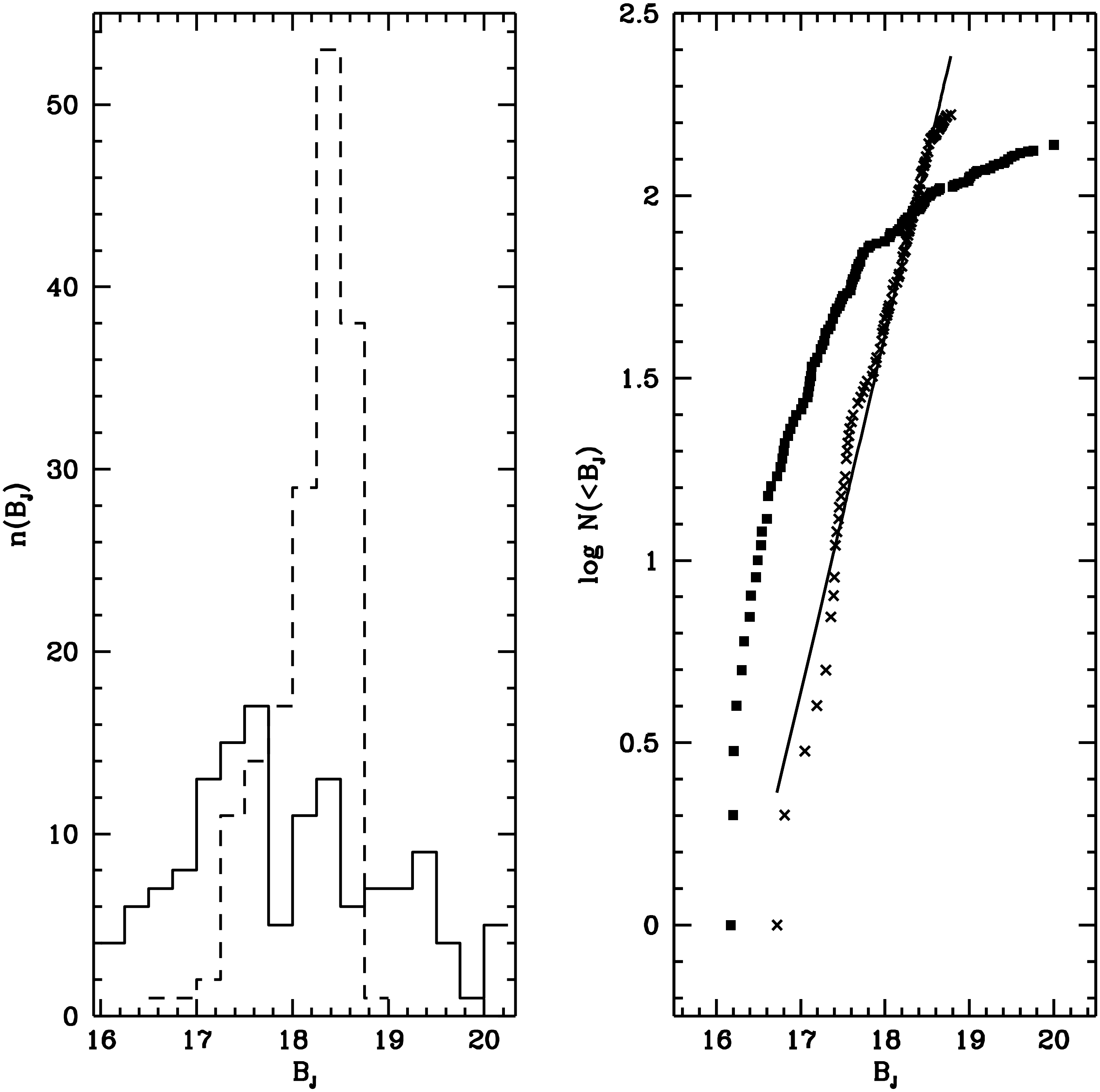
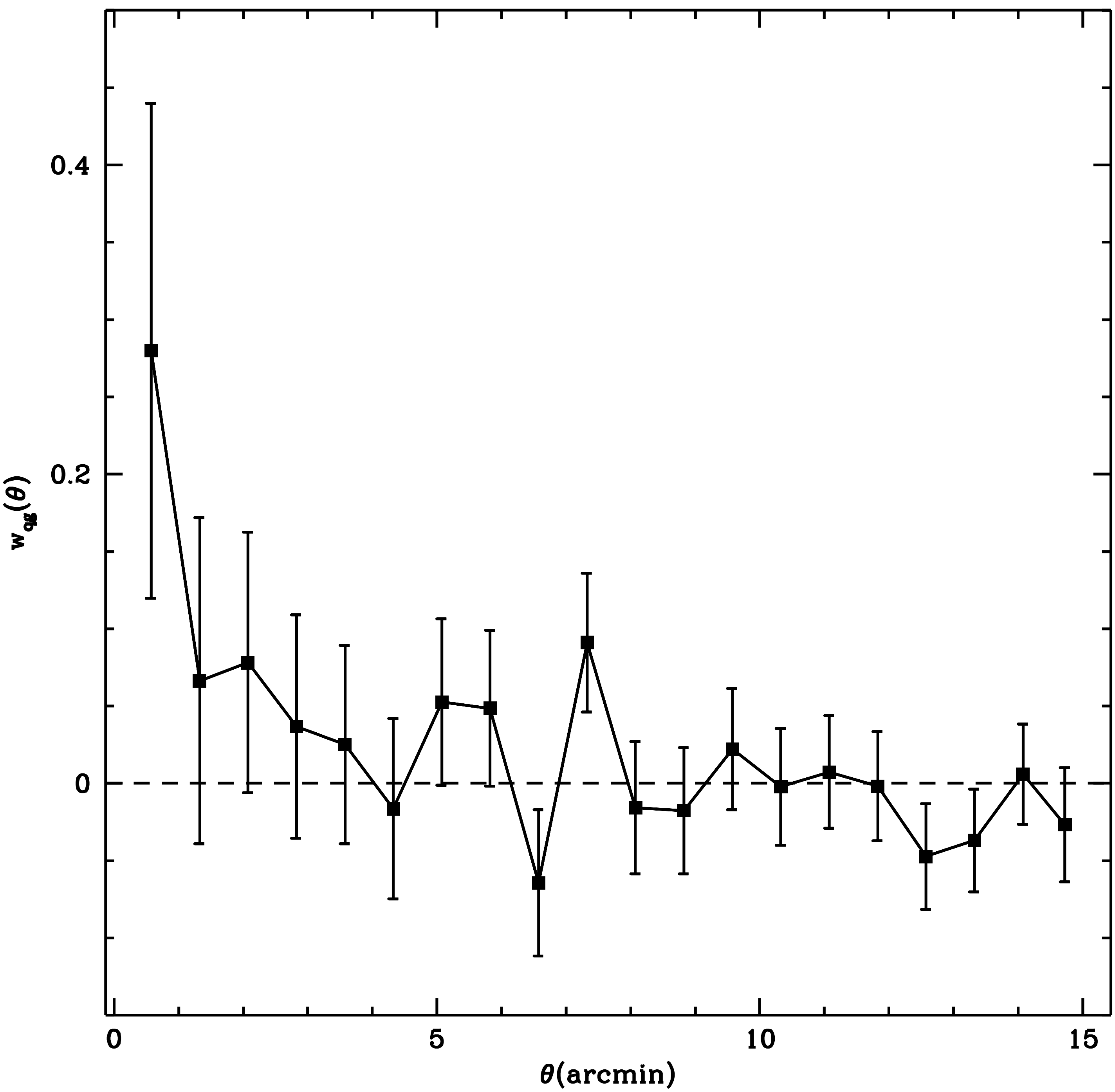
0
−0.1
−0.2
−0.3
$w_{qg}(\theta)$
0
5
10
15
θ(arcmin)


log N(>S)
log S
0
0.5
1
1.5
2
−0.2
0
0.2
0.4
0.6
0.8



n(B_J)
B_J
log N(<B_J)
B_J



0.4
0.2
0
$w_{qg}(\theta)$
0
5
10
15
θ(arcmin)